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SPUTNIK METEOROLOGY

M. S. Malkevich

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ABSTRACT

Uses of AES in meteorology as advantages over ground stations are discussed. Problems such as spectral analysis and atmosphere probing, cloud cover investigation and radiant energy flow, Earth temperature, atmospheric transparency, and atmospheric temperature and humidity profiles are examined.

The history of science contains many instances where new advances or new methods of investigation have revolutionized different areas of human endeavor and quickly found use in resolving practical problems including those unresolvable by existing methods. Therefore it is not unusual that launching artificial Earth satellites (AES) and spacecraft has resulted not only in a great increase in space sciences, but satellites have found application also in some purely "earth" sciences. Physics of the atmosphere and meteorology, which study processes existing in the Earth's atmosphere and explaining weather variability, are included in these sciences. The character of these processes always has demanded global study methods, which is exactly what artificial Earth satellites can offer. /31*

*Numbers given in margin indicate pagination in original foreign text.

Value of Weather Satellites

Use of satellites in meteorology has at least two properties. First, they permit rapid, simultaneous, and world-wide reception of information on atmospheric conditions and processes. Such data present the complicated mechanics of appearance and disappearance of atmospheric formations responsible for difficultly forecastable variations in weather. Second, it is equally easy for satellites to observe either inhabited territories with their diverse networks of weather stations or great stretches of oceans, deserts, forests, or polar regions occupying 86-90 percent of the Earth's surface and considered "white spots" in meteorology.

We should note that use of satellites is economically better than broad networks of ground weather stations, not to mention the practical impossibility of placing stations in ocean areas or polar regions.

Problems of Satellite Meteorology

Meteorology is interested in characteristics of the state (temperature, humidity, pressure, wind velocity) of lower layers of the atmosphere to heights of 30-50 km. Satellites fly at substantially higher altitudes, not less than 200 km. How, then, can we measure meteorological elements of the lower layers of the atmosphere with satellites? Apparently all information on characteristics of the state of the lower layers of the atmosphere can be obtained by measuring Earth radiation in various regions of the spectrum. It is known that astrophysics has long used spectral analysis to study star and planet atmospheres. However, in spite of external similarities there are many differences in presentation of the problem in astrophysics and meteorology. /32
Astrophysics considers primarily the content of various substances and evaluation of amounts of their concentration or temperature.

The Earth's atmosphere has been rather well studied. Average data for most meteorological elements are known for many regions of the planet and for the various seasons. Meteorologists must know variations in these elements in time and space, since it is they which affect and determine Earth weather irregularities. It is quite clear that determining variations in weather elements demands high accuracy of Earth's radiation and careful analysis of these observations. Much direct-measurement information on weather elements obtained by radiosonde probing of the atmosphere from weather station networks is an aid. This material can be used as additional information for a basis to obtain theories on the structure of fields of weather elements.

Besides determining meteorological elements, television on a satellite shows cloud cover formation (figs. 1 and 2). Clouds are the visible form of dynamic processes in the atmosphere. On the day side of Earth they are clearly visible on the background of the darker water or land and ice surface (against snow they are less clear). Cloudiness can also be recognized on the nocturnal side of Earth by contrast with the cloud irradiation itself and Earth's surface in the infrared spectral region. Clouds are "darker" due to temperature and therefore irradiation of its upper border will be less than the temperature and irradiation of the warm surface over ground or oceans.

Finally, satellites are used for measuring flow of radiant energy the Earth loses from reflected solar radiation and its own radiation into free space. Since solar energy flow to the upper boundary of the atmosphere is known rather closely (its quantity is practically constant and equal to $2\frac{\mathrm{cal}}{\mathrm{cm}^2\mathrm{min}}$), these measurements can determine energy remaining on Earth, as the difference of falling and escaping radiation. This difference finally is the single source of energy aiding all processes in the atmosphere, hydrosphere /33 and biosphere.

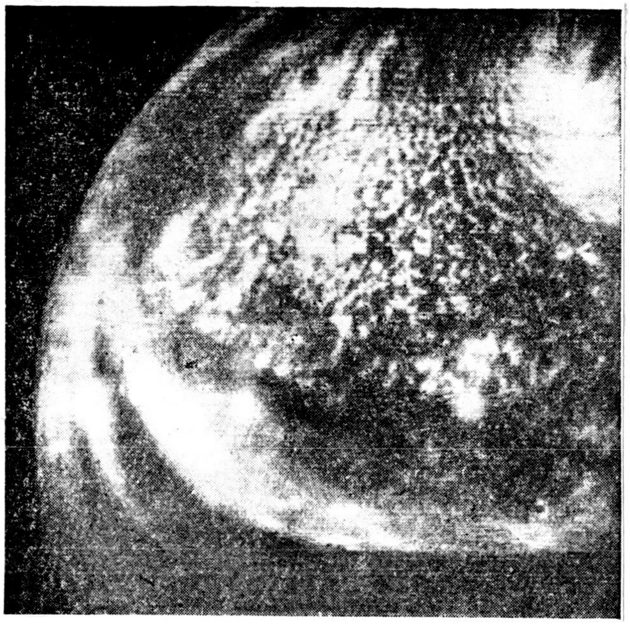

Figure 1. Cloud system as part of cyclone. Photograph shows cellular structure of cumulus clouds.

We calculated three basic problems of atmospheric physics resolvable by satellites at present. Naturally, each problem presents many difficulties due to complicated investigation phenomena and relative incompleteness of present study methods. This is more graphic in familiarization with methods of determining certain concrete problems of satellite meteorology.

Determining Temperature of Earth's Surface and Cloud Cover

Because Earth's surface temperature is ± 200-300°K, radiation energy is almost all distributed in the 3-40 μ spectral region with maximum radiation in the 8-14 μ region. We can measure Earth's own radiation and thereby determine its temperature through a satellite-mounted radiometer aimed toward Earth and having a narrow view angle (fig. 3). This temperature, called radiation, will differ noticeably from the true temperature obtained with the same radiometer

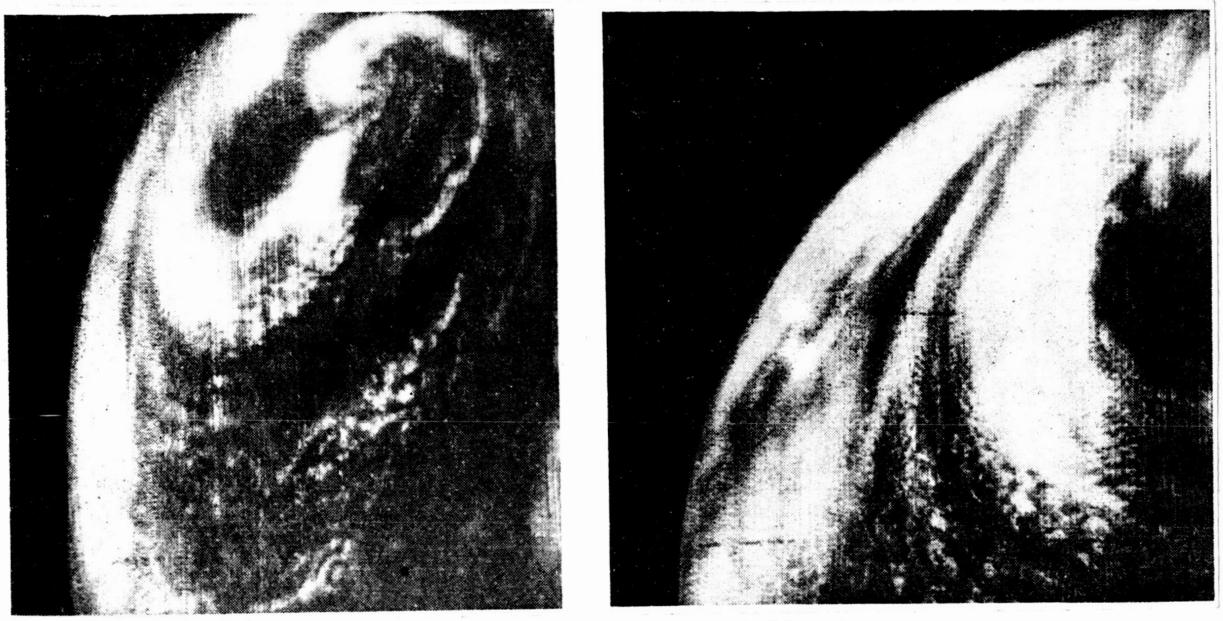

Figure 2. Clouds in storm and neighboring region as in figure 1, taken days later.

close to the Earth's surface. Differences between radiation and true temperature of Earth's surface (or, as expressed in meteorology, the lower layer, i.e., ground, water, snow, forest, etc.) reach 20^{o}. The problem is that all radiation of this bottom layer goes into cosmic space. It is greatly absorbed by the atmosphere (and water vapor, CO_2 and ozone in it) and is reirradiated by the atmosphere but with different temperatures (we must remember that air temperature drops $6\text{-}7^{o}$ each km). In some spectral regions ("transparency windows") the atmosphere absorbs weakly and equally weakly irradiates. Strictly speaking, there is no full atmospheric transparency in any spectral region. For example, in the 8-12 μ "transparency window" there are fairly many water vapor absorption lines and a heavy ozone absorption belt (fig. 4). It might be possible to remove more narrow "windows" with no absorption lines, e.g., 0.1 μ near 11 μ. Insufficient sensitivity of present radiometers allows no recording of such small energy. In daytime the 3-4 μ "window" is unsuitable, free from absorption

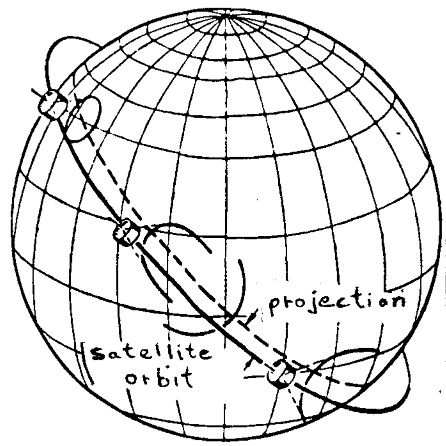

Figure 3. Coverage of Earth by satellite radiometer:

a, orbit projection; b, satellite orbit.

lines, since Earth's own radiation in this region is comparable to reflected solar radiation. Therefore on the day side of the Earth, over heavily reflecting surfaces or clouds the radiometer will measure total energy and the radiation temperature will be quite incorrect. On this basis the 8-12 μ "window" has been previously used in spite of distortions of the bottom layer radiation itself.

Thus, radiation measured directly on the satellite has two parts: that of the underlying layer and that of atmospheric radiation. Fundamental radiation from the lower surface by determined means depends on the Earth's surface temperature. /34 In space, this radiation is weakened by the atmosphere. The quantity characterizing this weakening is called the function of atmospheric passage and depends on the mass of matter absorbing the radiation throughout the atmosphere.

Fundamental atmospheric radiation can be presented in the form of the total of radiation from each layer with its temperature. In raising, radiation of each layer of the atmosphere is weakened at higher layers. The level of weakening depends on the concentration of absorbing matter. Temperature

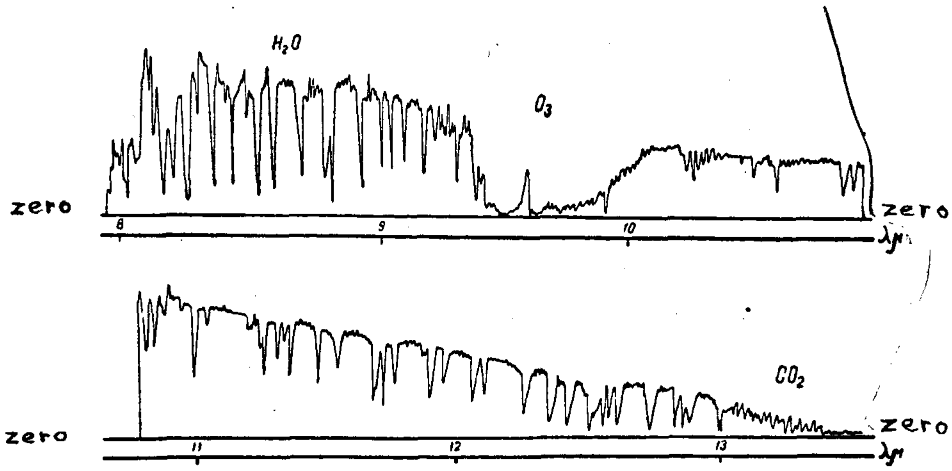

Figure 4. Appearance of solar spectrum in "transparency window" of atmosphere at 8-12 km showing multiple lines of water vapor and CO_2 absorption and heavy ozone absorption belts.

distribution and concentration by altitude continually change and at the moment of measurement remain unknown. Thus rigorous solution of the problem is not possible if simultaneous determination is not performed at least for vertical distribution of temperature and concentration of water vapor (calculating ozone absorption is relatively easy).

Here data on atmospheric temperature and humidity obtained by radio sounding in different regions of the Earth's sphere are an aid. We need only try using this material in the best way: to take what the atmosphere "retains" from all the information. Statistical development of data from these observations discloses the determined order in the structure of temperature and humidity distribution by altitude. First we can determine averages for many years for vertical profiles of these parameters ("norms") for a given region and interval. Also, correlations between temperature and humidity deviations from corresponding norms for various levels exist. With these characteristics of vertical structure of temperature and humidity fields we can obtain statistically improved approximate values for lower level temperature.

Now let us examine the atmosphere as any system at whose input a signal appears--study of the Earth's surface underlying the determination, and at the output signal distortions are measured--measurements of the Earth and atmosphere. Then the level of distortion of the input signal is characterized by the so-called atmospheric transfer function equal to the relation of output signal to input. The transfer function in the given spectral region depends on the vertical profiles of temperature and humidity. In the first approximation we can calculate the transfer function for temperature and humidity "norms." Then it is easy to obtain the first approximation of the input signal (irradiation of the underlying layer) dividing the output signal (the measured quantity) into this transfer function. Knowing the characteristics of the instrument, according to this approximation we can find the first approximation of lower level temperature. However, since average values of this temperature are also known, we have factually determined the first approximation for deviations of temperature from the "norm." Using correlations of this deviation on the under layer with deviations in temperature and humidity at other altitudes we find more probable values of these deviations. Such reduction of the function values on all points by the limiting number of its values is called the optimal extrapolation function. We thereby specify vertical distribution of temperature and humidity, permitting calculating the following approximation of the transfer function. With its help we can find a further approximation of the lower layer.

At first glance we see that, repeating the described cycle, we can approximate true distributions. We actually do not obtain true precision due to errors in determining lower surface temperature and establishing air temperature and humidity profiles with previous correlation values.

However, vertical temperature and humidity profiles can be more reliably determined by measuring certain supplemental characteristics of Earth irradiation in suitable spectral ranges.

Determining Vertical Profiles of Atmospheric Temperature and Humidity

Some atmospheric gases have known concentrations stable to high altitudes (CO_2 and oxygen). Thus, if we measure Earth radiation in absorption zones of these gases, only air temperature will be the unknown quantity radiation depends on. Moreover, if radiation is measured in different parts of the absorption zones, temperature distribution by altitude can be found. Actually, in /35 the part of the zone where the atmosphere is sufficiently clear, radiation is determined by low-level atmosphere temperature. In comparison to mixtures in the less transparent regions, radiation is characterized by temperature of higher layers, since measuring lower ones is completely merged.

To resolve this problem we measure radiation in the CO_2 zone ($\pm$ 15 μ). Radiation in any spectral zone is the sum of radiation of one or another combination of various atmosphere layers. The contribution of each layer to total radiation depends on its temperature, which we must determine, and passage through the atmosphere, which is known, since CO_2 concentration in the atmosphere is practically constant. We must also consider that insufficient resolving ability of present spectral instruments results in the necessity to calculate overlapping of CO_2 zones by relatively weak water vapor absorption zones. Concentration of the vapor in the atmosphere is so changed that it is better determined at the same time as temperature. But even independent of this, water vapor concentration determination (specific humidity) at different altitudes has no less interest for meteorology than temperature determination.

Humidity can be determined by measuring water vapor radiation in its absorption zones, e.g., 6.3 μ, by using previous ways, but this time knowing the temperature of each radiating layer of the atmosphere. Passage of these layers, dependent on unknown water vapor concentration, is unknown.

Thus, both problems are closely interrelated. They must be decided in such an order: First by radiation measurements in the CO_2 region we determine temperature, ignoring water vapor absorption. Then humidity is determined by measurements in the 6.3 μ zone with the aid of obtained temperature. Next we can more narrowly determine temperature, calculating overlapping zones of CO_2 and water vapor in the 15 μ region, and then humidity.

Practical solution of both problems involves two inherent difficulties. First, we require high accuracy of radiation measurements within sufficiently narrow spectral zones (we remember that temperature and humidity variations are necessary for the Earth's atmosphere). Second, reliable determinations of temperature and humidity for various layers of the atmosphere from totals of their radiation are necessary.

Present measurement technology permits obtaining data with required accuracy (in any case, there are no principal drawbacks to this). Overcoming the second difficulty is complicated, because recovering temperature and humidity of the atmospheric layers from the total of their irradiations can lead to great errors and even to physically senseless results if we do not take necessary precautionary measures.

To avoid these errors we must use information on the vertical structure of atmospheric temperature and humidity fields.

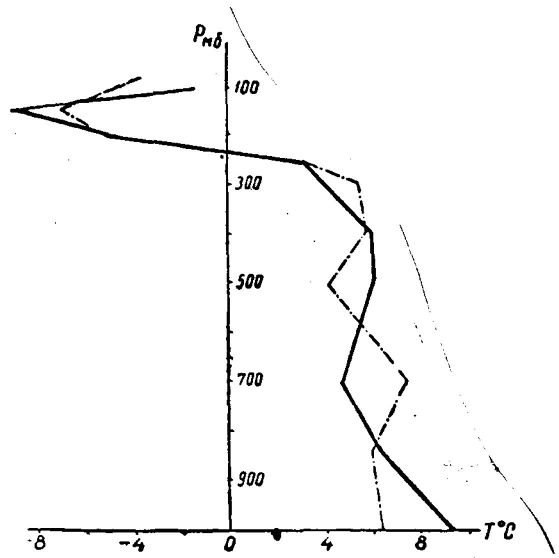

Figure 5. Sample of determining deviations from vertical profile of temperature from mean (solid line = true temperature, broken line = reduced).

Besides the already indicated correlative relations we can find such a system of characteristics of the vertical structure through which any temperature (or humidity) distribution can be best established. It appears that with such a system of characteristics we can provide establishment of determined quantities with least error. Precisely this circumstance permits obtaining reliable solution of the so-called reverse problem (in the given case the problem of determining temperature and humidity by investigation recorded by the satellite). Figure 5 shows effectivity of using characteristics of the vertical temperature field structure to determine its altitude pattern. Cited examples show that for effective use of satellites in meteorology many theoretical and experimental problems must be resolved.

However, even now it is apparent that weather satellites aid in obtaining such data as cannot in principle be recorded by even the most extensive network of ground stations.